Sulphur Mines Salt and Caprock Mapping Methodology

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Remapping of the caprock and top of salt surfaces was undertaken in 2023 using reprocessed 3D seismic data, the extensive existing well data base and reprocessed offset VSP data. The following data were used as input to the current mapping project.

Input Data

Well Data for Sulphur Mines were predominantly taken from the Petra database assembled in 2017 by Craig Tilley and Jerry Ferguson of Lonquist. These are the same data used for the 2017 Eagle Brine #25 application and for the updated salt map submitted to DNR as part of the 2020 Compliance Review for Sulphur Mines. There are about 600 wells in the database, including deviations surveys for many of the boreholes. For this current work we refined the deviation surveys by adding additional points to the trajectories using the original directional surveys available on the Sonris website. Salt penetrations for eight wells were added to the database based on salt tops reported in Whiting & Beasley's 1981 SPR report (Fee 840, 877, 890, 890st1, 895, 899, 933 and 942). Approximately 190 of the wells penetrate salt (see pink highlighted wells in Figure 1). Together this well database forms a tight set of boreholes that constrain the location of the salt flank, often more tightly even than the seismic traces.

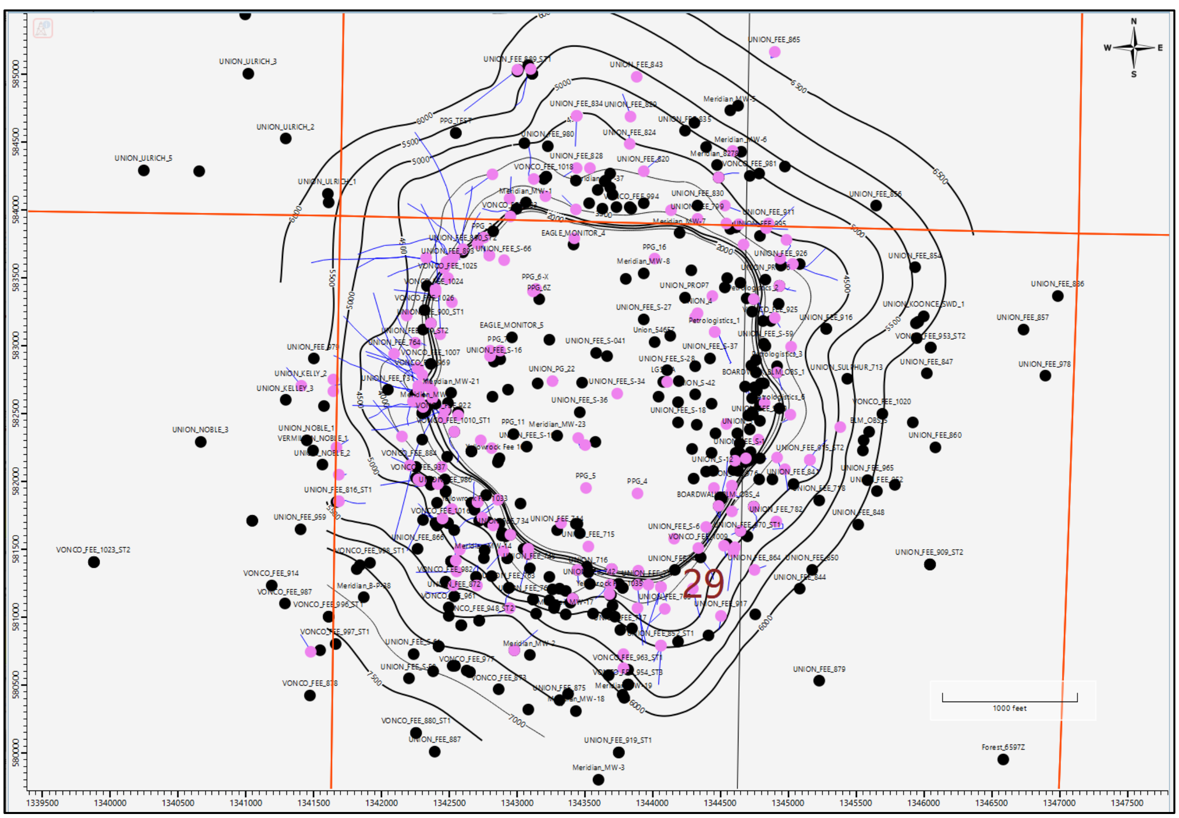


Figure 1. Sulphur Mines Well Control. Salt penetrations in pink

Older wells included in the database tend to have more uncertainty in their surface location and may lack directional surveys; in those cases we left the older wells in the database but during interpretation we preferentially favored newer well data when there was a contradiction in the well control.

As part of this 2023 study we re-examined 101 wells on the west side of the dome in the vicinity of Caverns 6 and 7. For each well we reviewed the available Sonris well files, updated the directional surveys with additional points as appropriate and made sundry minor improvements to the well database. 10 of those wells were identified as having previously unrecognized shallow layers of caprock/salt extending from the dome. Those wells are summarized below in Table 1.

API	Name	KB	X	Y	TD	Directiona	Year		Shallow Caprock?	Caprock	Salt	DNR
17019007530000	UNION_FEE_892	16	1342516	583631	2820	yes	1946	elog	2200-2470?		2796	31898
17019007600100	UNION_FEE_900_ST1	25	1342361	583168	3134	yes	1948	e-log	2718-2763?		3079	
17019212100000	UNION_FEE_957	32	1342819	583850	4162	yes	1983	elog	3604-3720		3840	186078
17019212540000	VONCO_FEE_968	31	1342770	581902	4173	yes	1983		1850-2150			189415
17019215570000	VONCO_FEE_1010_OH	33	1342549	582395	2965	yes	1988	density & e-log	1677-1821; 1847-1867; 1963-2268			207661
17019215920100	VONCO_FEE_1013_ST1	33	1342343	582705	4906	yes	1989	density only	poss caprock 2712-2850 & 2180-2336			
17019215950000	VONCO_FEE_1011	27	1342395	583402	4830	yes	1989	e-log	2440-3300	4453	4595	209458
17019215960000	VONCO_FEE_1012	32	1342373	582619	3524	yes	1989	e-log	2640-2875			209459
17019216190000	VONCO_FEE_1017	33	1342375	582669	4535	yes	1989	dens only	2696-2733; 2770-2851			210185
17019223030000	VONCO_FEE_1025	28	1342488	583504	5218	yes	2012	quad	3120-3280		4996	244876

Table 1 Ten wells with previously unrecognized shallow caprock/salt

VSP Data As part of this study we reprocessed the available single-offset VSP dataset that was recorded in 2004 in the Vonco Fee 1016 well (Well Serial #210026). The well was equipped with receivers over the range of 462-4950' tvd, while the single source location was located on the edge of the Cavern #7 wellpad (see Figure 2).

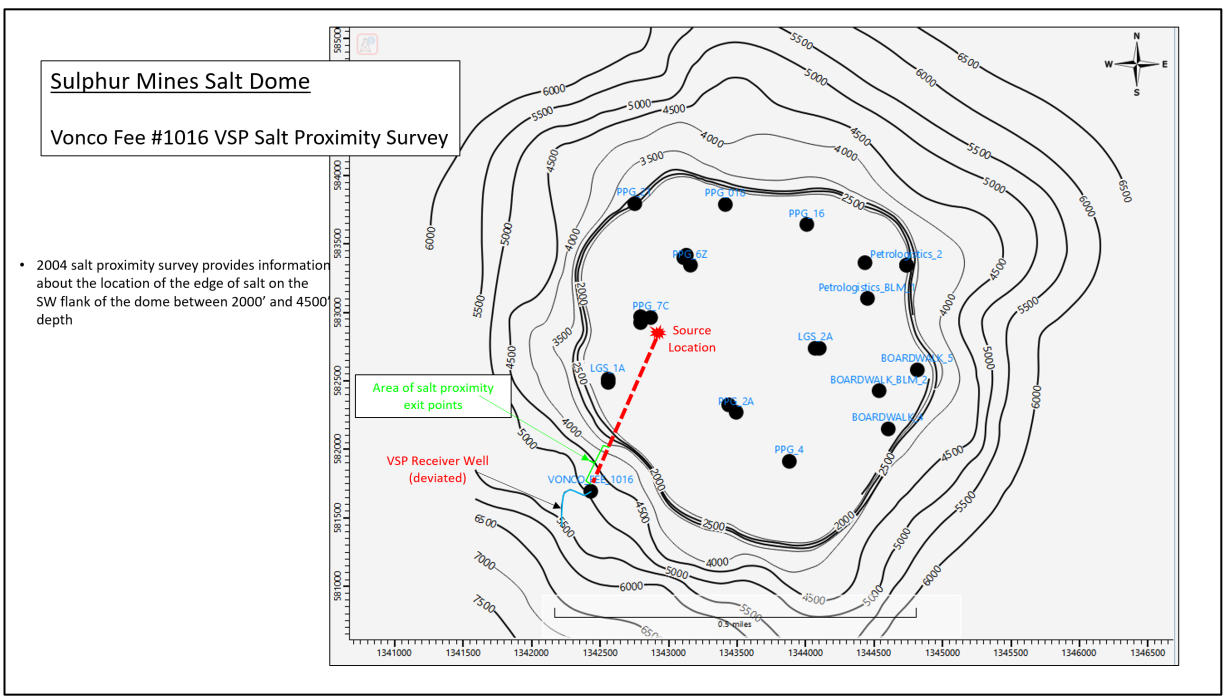


Figure 2 Vonco Fee 1016 Offset VSP geometry.

The VSP recording geometry was such that raypaths from the source passed either directly through sediment to the shallowest receiver depths, or refracted through the caprock and salt, before exiting into sediment and being recorded in the deeper receiver locations. The VSP reprocessing provided us with updated 3D xyz locations of those exit points from caprock/salt. Those exit points indicated that a fast layer of caprock/salt extends outwards from the salt dome some tens of feet to intersect the Vonco Fee 968 well (Well Serial #189415). at approximately 1900' depth. When we examined Fee 968 we did in fact discover a caprock/salt layer that had not been previously documented (Figure 4).

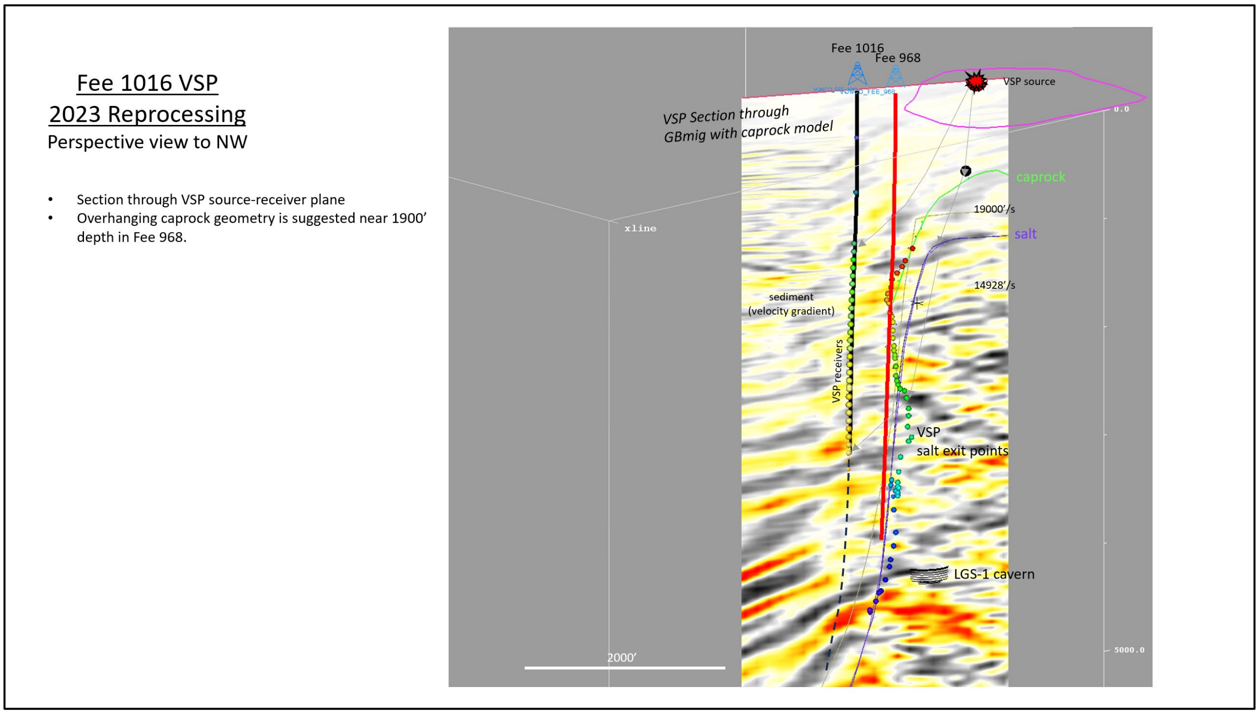


Figure 3. Vonco Fee 1016 VSP Results

The results of the VSP reprocessing showed that:

(1) the overall shape of the salt dome in the vicinity of Fee 1016 and cavern LGS-1 was similar to previous interpretations, but the reprocessing added confidence to the interpretation;
(2) mapping of the fast caprock geometry was important to an accurate positioning of VSP caprock/salt exit points. We used this result to influence the velocity model used to correctly position the 3D surface seismic which was being reprocessed at the time, in much the same way that the detailed sediment velocity field from 3D surface reprocessing was used to improve the accuracy of the VSP results.
(3) minor bulges in the caprock/salt surface can extend out into the flanking sediment by some tens of feet. This led us to re-examine the well logs and wellfiles for the 101 wells on the west side of the dome (as described above), leading to the discovery of the additional 10 wells that intersect caprock or salt on the steep flanks of the salt dome.

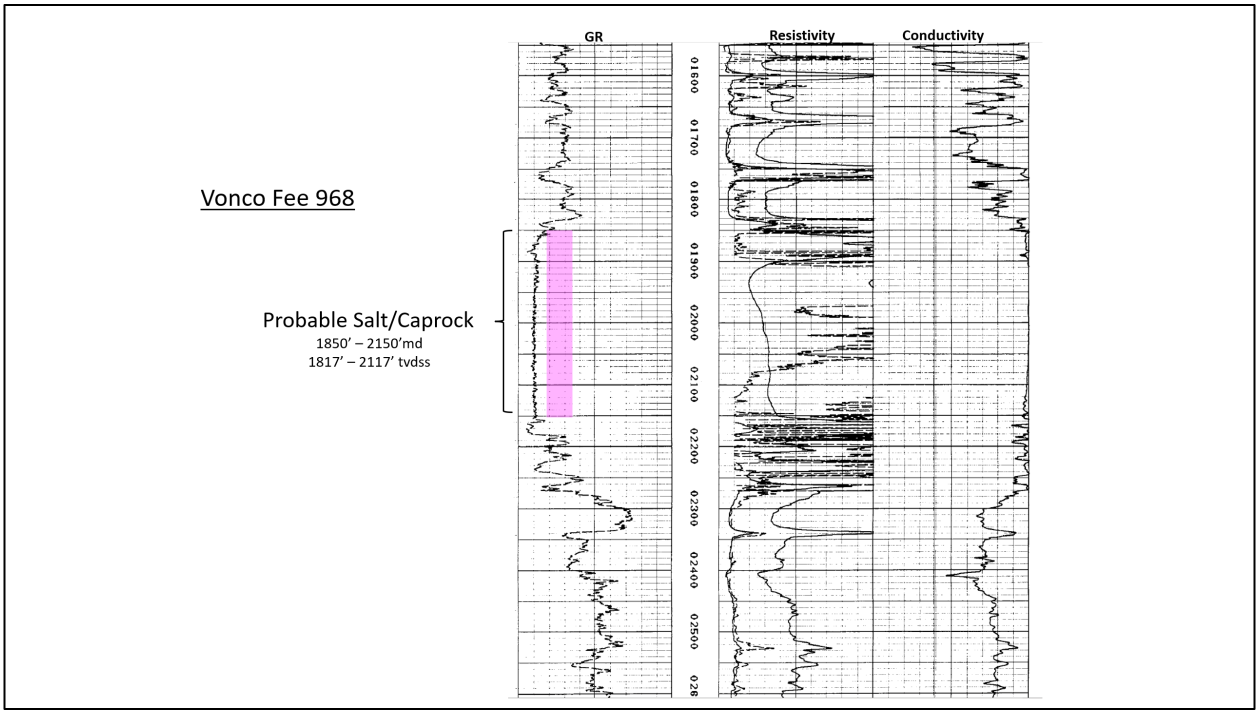
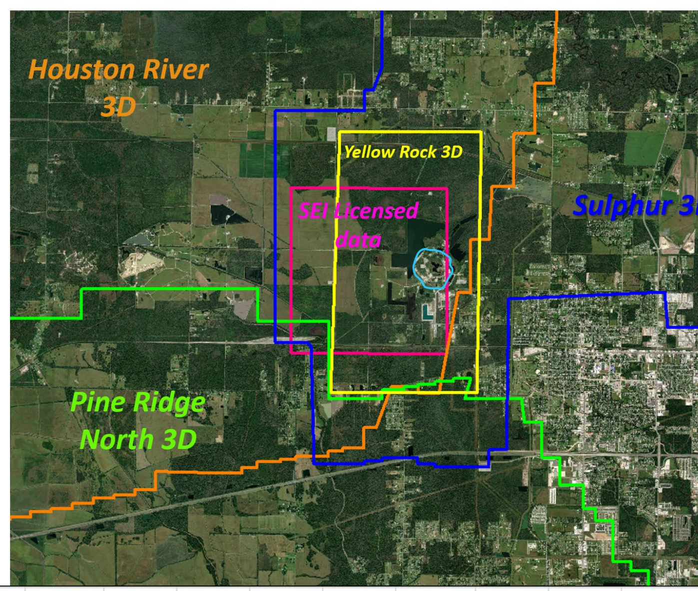


Figure 4. Vonco Fee 968 with previously unrecognized caprock/salt interval

3D Seismic Data

SEI 3D Data Map

- Data were recorded in 1998 and 2009 with acquisition parameters that are typical for the O&G industry
- Houston River 3D and Sulphur 3D are the main contributors to fold on the west half of the dome
- Pine Ridge North 3D had only minor contribution
- Data were processed on 110' x 110' bins
- (Yellowrock 3D was not included in the processing)



Survey	Date Shot	Crew	Bins	nline Offse	(-Line Offse	Max Offset	Fold	Source	Source Int	Sx Line Int	Receiver In	Rx Line Int	# Rx Lines	# Rx per line
Houston River 3D	Jan 2009	CGG	110x110	24090	8470	25,801	90	Pentolite	492	2200	220	1540	12	220
Pine Ridge North 3I	Apr 1998	Grant	110x110	16390	5940	17,668	96	Dynamite	220	1100	220	1320	10	150
Sulphur 3D	Jan 1998	Grant	110x110	13090	7260	15,393	~54	Dynamite	220	~1320	220	1320	12	120

Figure 5. 3D seismic surveys that contributed to the 2023 RTM reprocessing

The seismic data used in the 2023 study was a merging of three contributing 3D seismic surveys that were recorded over or near the Sulphur Mines salt dome. As illustrated in Figure 5, Houston River 3D, Sulphur 3D and Pine Ridge North 3D were recorded in 2009, 1998 and 1998 respectively with acquisition parameters that were typical for the oil industry at the time. The three surveys (along with many other surveys) had been reprocessed and merged by Seismic Exchange in 2019 to create one large merged 3D seismic data named 'Alligator Merge'. Examination of the Alligator Merge showed us that the pre-stack time migration (PSTM) used in that merge was inadequate to properly image the salt dome.

Based on ray-tracing, we selected a 5 square mile area for reprocessing using a more advanced depth migration algorithm called 'Reverse Time Migration'. That 5 square mile area is outlined in magenta in Figure 5; it covers approximately 85% of the west side of the salt dome (where Westlake's operations are located), but does not cover the easternmost flank. (Note that the shown Yellow Rock 3D was not available to be included in this reprocessing.) Seismic reprocessing, including RTM imaging, made major improvements to the image quality of the west flank of the salt dome. The final version of RTM migration was subsequently used for the updated mapping of the caprock and salt surfaces.

Caprock and Salt Interpretation

Picking the top of salt and top of caprock seismic horizons requires careful visualization and data integration of the available 3D seismic data, VSP data and well control. At Sulphur Mines the interpretation procedure was conducted in an iterative manner. An initial salt model was used for the preliminary Kirchhoff pre-stack depth migration (KPSDM) sediment flood. The second and third processing iterations included caprock and salt picks for the first salt flood migration and the final RTM respectively. Three final iterations of salt picking and caprock picking of the final RTM were completed to produce the final salt and caprock interpretations.

Figure 6 illustrates the first step in the picking workflow. Every vertical inline and crossline section was picked for salt (and caprock) fault lines. Fault lines have a more robust topology than traditional horizon grid picks because fault lines can accommodate a curve that doubles back on itself, as occurs when salt is overhanging; normal horizon grids cannot accommodate the multiple depth values (multi-Z values) of vertical and overhanging surfaces.

At Sulphur the salt is defined on seismic predominantly by the abrupt loss of continuity of the flanking sediment reflections (i.e. not on an explicit salt reflection as is seen on some other salt domes). We believe the lack of a discrete salt reflection at Sulphur may be caused by small velocity inversions observed in the flanking sediments; those inversions refract the diving raypaths that would otherwise illuminate the steeper parts of the salt face. The caprock seismic pick is similarly defined by the loss of flanking sediment reflections, although in places the shallow caprock does generate a small peak. In general, caprock seismic illumination is limited by the lack of source and receiver points acquired over the top of the dome. For both salt and caprock picks the well control is so dense that it provides a tighter constraint on the interpretation than the seismic does on its own, especially on the steep flanks of the dome above 5000' depth where well control is most prolific

3D Seismic Interpretation

- Each inline and crossline over the dome was interpreted for edge of salt
- This process was run three times during processing and another three times during interpretation, steadily improving the final product

Perspective view down to the ESE

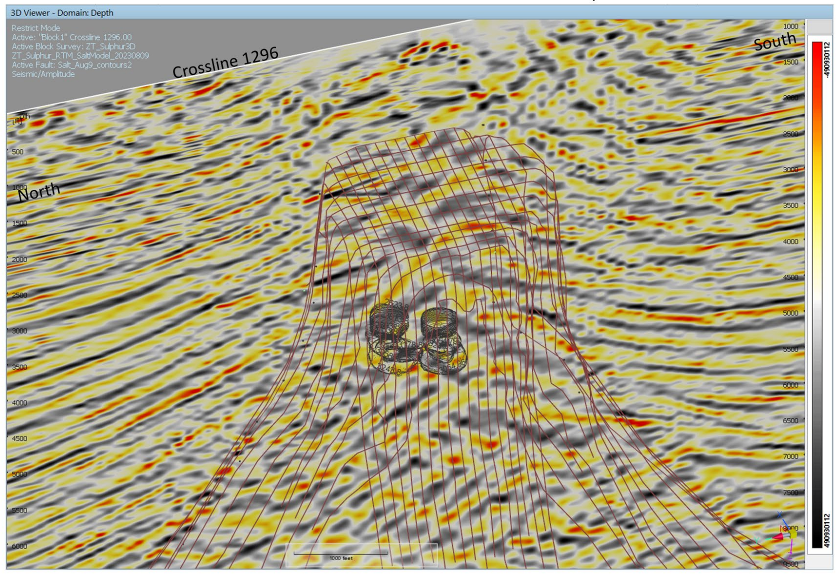


Figure 6. Inline and Crossline Salt 'Fault' Interpretation

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3D Seismic Interpretation

- Each inline and crossline over the dome was interpreted for edge of salt
- Contours (green) were interpreted, consistent with well salt picks (magenta)

Perspective view down to the ESE

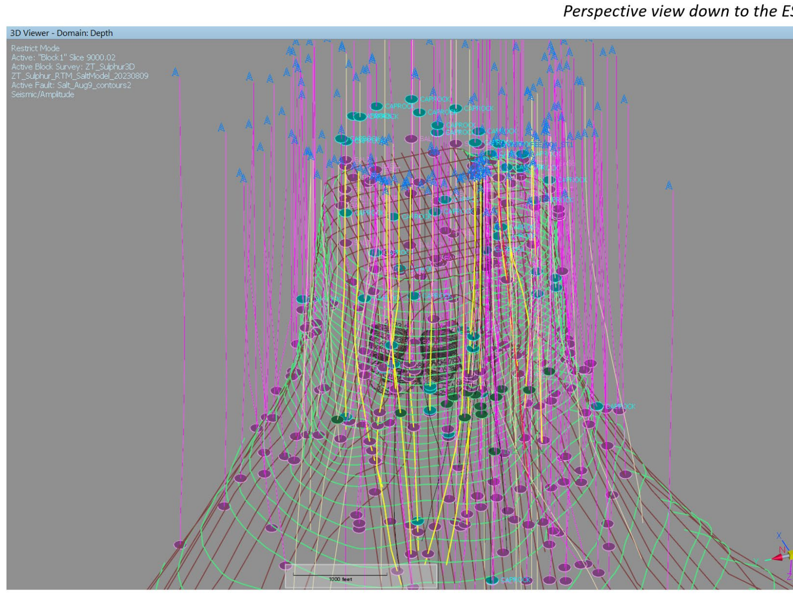

Figure 7. Depth Slice Salt 'Fault' Contour Salt Interpretation

The second step in the picking workflow is to re-pick the salt surface as fault lines on depth slices through the 3D seismic volume. This allowed us to smoothly contour the surface in 3D while honoring both the seismic signature and the well control, which includes both specific top of salt picks along with negative control along the wellbores above salt that define where the salt is not present. This approach also assures that there are no crossline mispicks in the interpretation because the depth slices do not intersect one another. In Figure 7, wells are shown in 3D perspective view as magenta deviated boreholes with cyan and magenta disks representing the 3D xyz locations of the caprock and salt intersections respectively. The brown lines are the inline and crossline salt fault picks from Figure 6. Contours (lime green) were picked on every 100’ seismic depth slice from 1500’ to 5000’ tvdss.

Figure8 shows the same perspective view as Figure 7 but with the addition of the caprock picks in cyan.

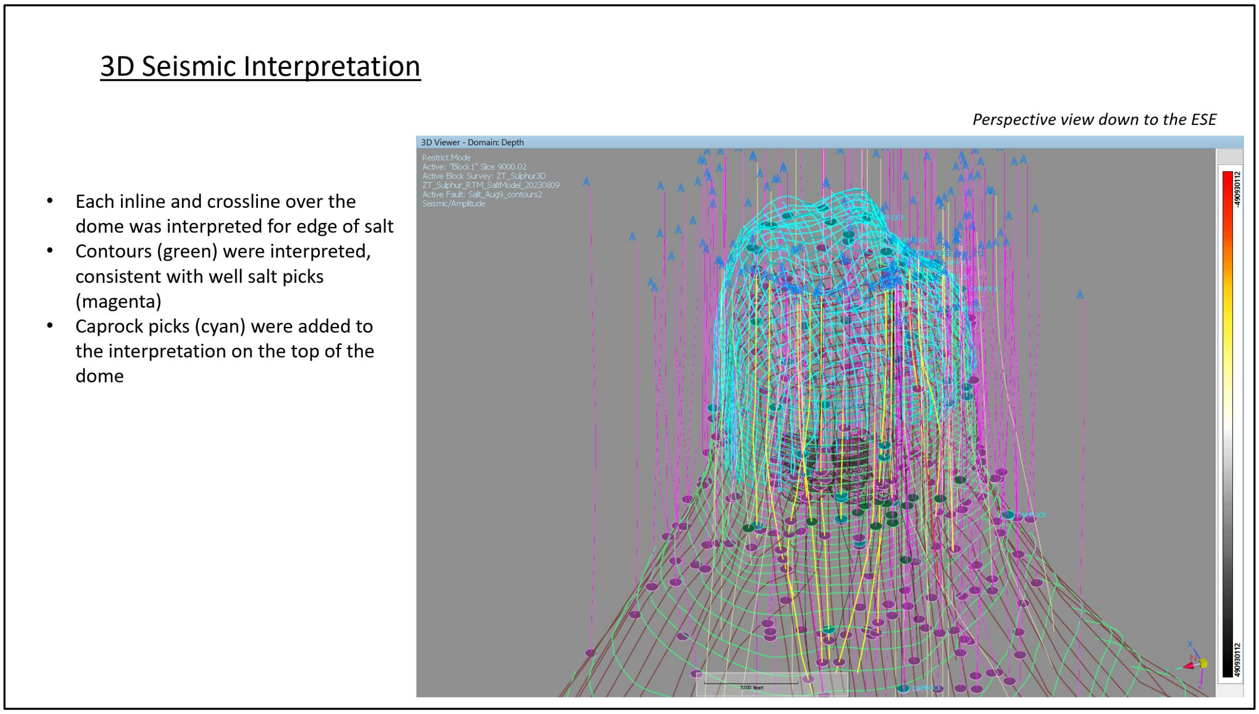

Figure 8. Depth Slice Salt ‘Fault’ Contour Caprock Interpretation

The third step in the workflow is to link the depth contour fault lines via tessellation to form a triangulated surface, including overhangs. Figure 9 shows the tessellated salt surface, colored by depth, and displayed with the roughly flat top of salt surface removed for illustrative purposes.

3D Seismic Interpretation

- Each inline and crossline over the dome was interpreted for edge of salt
- Contours (green) were interpreted, consistent with well salt picks (magenta)
- Caprock picks (cyan) were added to the interpretation on the top of the dome
- The salt interpretation was tessellated into a triangulated surface, honoring overhanging panels

Perspective view down to the ESE

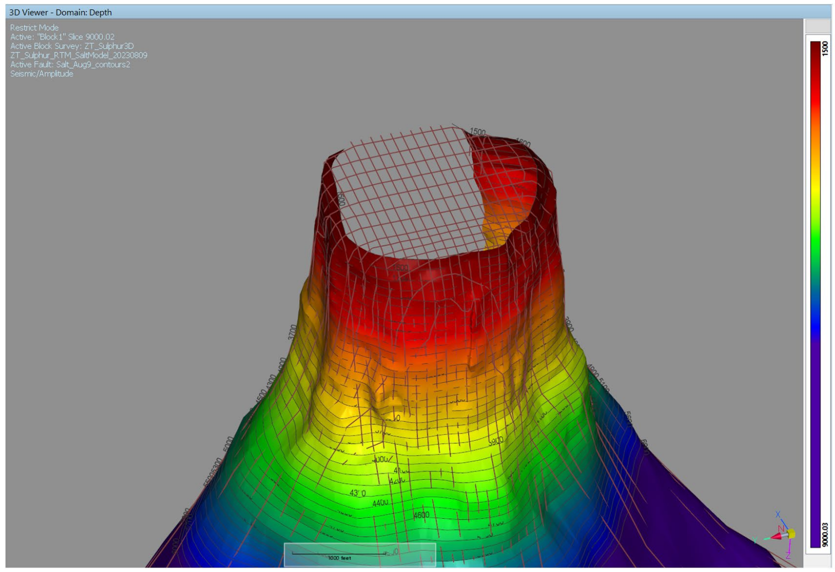

Figure 9. Tessellated Salt Interpretation

To create a final display contour map, the salt and caprock surfaces were re-contoured using standard contouring software to output contours at the desired contour interval (Figure 10). Of course, a contour map is a limited way to view a complex 3D object such as a near-vertical salt dome, because the contours tend to overrun one another in map view.

We ran a statistical analysis of the 3D match between the final salt surface interpretation and the input well data. The analysis showed that the wells and final seismic-influenced salt interpretation match to within 25’ laterally, between 1500’ and 4000’ on the west side of the dome. We conclude that the approximate horizontal accuracy of the final salt flank interpretation is ±25’ horizontally and approximate vertical accuracy is ±50’. These results are comparable to a similar study at the White Castle salt dome (Thompson and Loof, 2021).

For the Sulphur Mines remapping project the salt and caprock seismic interpretations were made in 3D Integrated Canvas, dedicated geoscience interpretation software licensed from Aspentech (formerly Paradigm Geophysical).

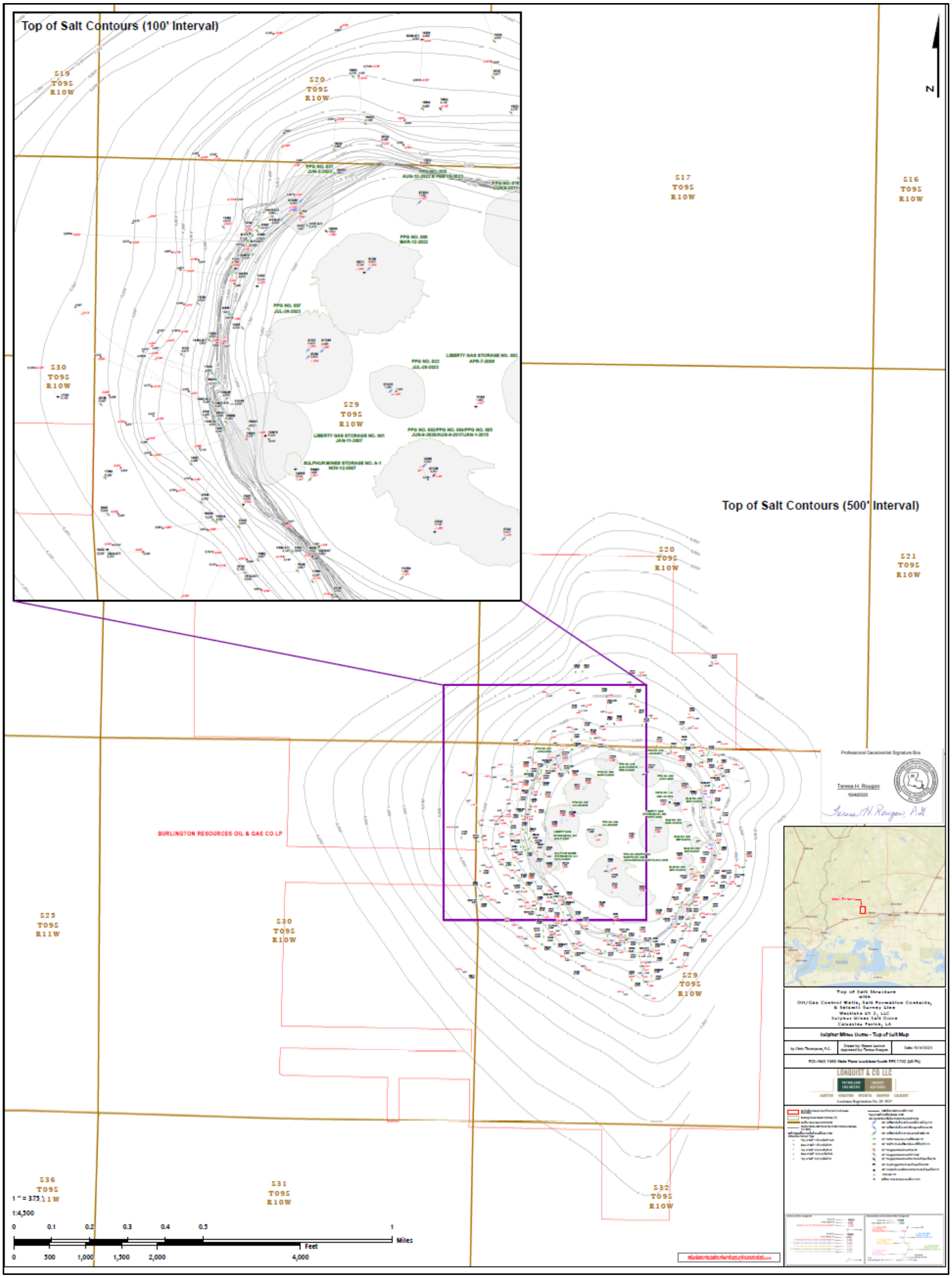

Figure 10. Top of Salt Contour Map

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